REPORT NO. P64-70

DEVELOPMENT OF DIELECTRIC WINDOWS FOR SPACECRAFT ANTENNAS

Final Report Covering Period
1 July 1963 to 30 June 1964

AEROSPACE GROUP
HUGHES
HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

DEVELOPMENT OF DIELECTRIC WINDOWS FOR SPACECRAFT ANTENNAS

by

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Final Report Covering Period
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Contract NAS 8-11026
Control Numbers TP 3-85485 and CPB 02-1251-63

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama

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FOREWORD

This report was prepared by the Hughes Aircraft Company under contract number NAS 8-11026, "Development of Dielectric Windows for Spacecraft Antennas," for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Propulsion and Vehicle Engineering Division, Engineering Materials Branch of the George C. Marshall Space Flight Center with Mr. E. C. McKannan acting as Project Manager.

CONTENTS

ABSTRACT

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Criteria were chosen for the selection of candidate dielectric window materials and seven types of reinforced plastics and two ceramics were chosen for the screening evaluation.

The candidate materials were subjected to a series of screening tests, included the degree of vacuum stability, the effect of ultraviolet radiation on the solar absorptance and dielectric properties and the gas permeability. Methods of decreasing the gas permeability, including lamination with plastic films and resin impregnation, were investigated.

The effect of thermal control coatings on the dielectric properties of a standard plastic radome material was investigated.

INTRODUCTION

The principal objective of this program is the development and qualification testing of reinforced plastics and ceramics for the fabrication of radomes for spacecraft antennas. These materials must be low in dielectric loss, heat-resistant, strong, rigid, creep resistant, low in permeability to gases, and reasonably stable to the space environment.

No one material can be expected to be ideal in all respects. Compromises will have to be made and materials of composite construction will be required to meet all of the requirements.

For example, a plastic radome with good dielectric and strength properties but high permeability to gases can be laminated to a plastic film with low permeability. An alternate method consists of the impregnation of a cured plastic with a compatible resin system.

A strong, electrically acceptable, impermeable radome with undesirable thermal radiative properties can be coated with a thermal control coating with the desired thermal radiative properties. This thermal control coating will also protect a radome material with poor resistance to solar radiation. Thus, a typical composite radome may consist of the basic radome structure with a low permeability membrane laminated to the inner surface and a thermal control, protective coating on the outer surface.

All the plastic radomes will consist of heat resistant plastics reinforced with glass cloth. The type of glass used can be one of several types (E glass, S glass, D glass, quartz) depending on the properties desired. The RF transmission loss can be minimized by the use of a low loss cloth reinforcement made from D glass or quartz. The degree of improvement of the dielectric loss will be greater for lower loss plastics. The low loss reinforcements now available also have low values of dielectric constant compared with E glass or S glass. Therefore, radomes containing these low loss reinforcements will be thicker than corresponding radomes containing E glass or S glass.

All of the plastics being considered in this program are highly heat-resistant. These materials are routinely post-cured to develop

optimum physical properties for long periods at temperatures ranging from 500° to 800°F. Sterilization by baking an additional 24 hours at 300°F should cause no further change in the physical properties.

A plastic radome of the half-wave wall type can possibly be utilized as an ablative heat shield for an antenna structure during entry into the Mars atmosphere. It has been estimated that less than 0.200 inch of reinforced plastic ablative material would be required at the extreme front of a vehicle during a typical Mars entry. This is somewhat less than the half-wave thickness for any of the reinforced plastics under consideration.

CRITERIA FOR MATERIAL SELECTION

ELECTRICAL PROPERTIES

The most important properties to be considered in evaluating any material for a radome application are its electrical properties including the dielectric loss, the temperature dependence of dielectric properties, and the dielectric constant.

The dielectric loss is the most important electrical property contributing to radome efficiency. The loss of electrical energy in a radome-antenna system, however, is brought about by many phenomena other than the simple conversion of RF energy to heat which is a function of the dielectric loss of the material. Other sources of electrical loss include those associated with the antenna design, interactions between the antenna and radome and multiple reflections from radome surfaces. The relative magnitude of the electrical loss attributable to dielectric loss in the material and to other causes will dictate to some extent the maximum allowable dielectric loss in a candidate material for a specific radome application. In general, the dielectric loss should be kept as low as possible with values for the dielectric loss tangent of 0.01 or less considered desirable.

Since the radome for a spacecraft antenna will be expected to operate over a fairly wide range in temperature, the temperature dependence of dielectric properties of candidate materials must be considered. This is particularly important in the design of a half-wave wall type radome, but not nearly as important in the design of a so-called "zero wall" radome. The temperature dependence of dielectric loss must be sufficiently low in high-power applications to preclude the occurrence of a regenerative process in which RF heating in the radome wall increases the temperature and therefore the dielectric loss which results in further RF heating. This process continues until a temperature is reached which destroys the radome. The temperature dependence of the electrical thickness which is a function of the temperature dependence of dielectric constant and the thermal expansion must be kept below some maximum allowable value over the specified temperature

range depending on the particular antenna-radome system and the required performance.

The dielectric constant would be considered the least important of the three since, in practice, the dielectric constant of a material may vary between relatively wide limits for the material to be considered for the fabrication of a half-wave wall type radome. This is so because the thickness of a radome of this type is approximately inversely proportional to the square root if its dielectric constant.

STABILITY IN SPACE ENVIRONMENT

Only those materials were evaluated which are known to have sufficient heat resistance to withstand the expected range in operating temperature. The upper temperature limit of 350°F narrowed the list of potential plastic materials considerably to the silicones, phenylsilanes, heat resistant polyesters, and a few relatively new experimental resins such as polyimides, diphenyl oxides, and polybenzimidazoles.

The degree of vacuum stability of each of the materials under consideration was determined. The results indicate that special preconditioning procedures will probably have to be adopted to stabilize some of the plastics to a hard vacuum-high temperature environment.

The resistance of the proposed radome material to ultraviolet radiation is not considered to be as important as the electrical properties and high temperature vacuum stability, since protective coatings may be used to exclude effectively all incident ultraviolet radiation. The thermal control coatings for achieving temperature control would also prevent deterioration of a radome substrate from ultraviolet radiation.

SEALING ABILITY

Since, in this application, the radome wall itself will be expected to act as a fairly effective gas barrier, the gas transmission of each reinforced plastic candidate material must be measured. It is not expected that any difficulty will be experienced in obtaining completely leak-free ceramics. The gas transmission will depend on the amount of gross leakage through cracks and pores and on the gas permeability of

the material itself. Most of the laminated plastics being considered in this program will be porous to a degree and it is expected that virtually all gas transmission will be due to gross leakage. Impregnation or coating with a suitable resin or lamination with relatively impermeable, leak-free films can be used to reduce the gas transmission of any of the candidate materials to an acceptably low value.

Sealing of the radome structure to the spacecraft will best be accomplished by first sealing the radome to a metal mounting ring with a structural adhesive. This radome ring assembly will then be sealed to the spacecraft using a sealing method appropriate for achieving metal-to-metal seals.

THERMAL RADIATIVE PROPERTIES

The thermal radiative properties will be controlled, if necessary, by the use of thermal control coatings. Therefore, the solar absorptance and infrared emittance of the various candidate materials are considered to be relatively unimportant compared with dielectric properties, heat resistance, and vacuum stability. As mentioned previously, a thermal control coating would also shield the substrate from ultraviolet radiation.

STRUCTURAL EFFICIENCY AND ELECTRICAL CONSIDERATIONS

The strength-to-weight ratio of most types of reinforced plastic laminates is known to be high and this property is considered to be the least important in choosing materials for evaluation. A half-wave type radome must be fabricated from a material with excellent electrical properties over a wide temperature range. All of the fiber glass reinforced plastics considered in this program have far greater strength properties than required for the fabrication of a half-wave type radome.

The fabrication of a thin-walled, so-called "zero wall" radome can also be considered. Perfect transmission (assuming zero loss) will be obtained through a dielectric sheet at an angle θ if the thickness is

$$d = \frac{n\lambda_o}{2\sqrt{\epsilon - \sin^2\theta}}$$

where ϵ is the dielectric constant of the dielectric sheet, λ_o is the free space wavelength and n is any positive integer. A thin sheet of dielectric can be considered an approximation to a half-wave sheet of order zero. The actual electrical thickness expressed in wavelengths is given by

$$d_e = \frac{d\sqrt{\epsilon - \sin^2\theta}}{\lambda_o} .$$

The electrical thickness depends on the physical thickness, the frequency, the dielectric constant and angle of incidence. Sheets with an electrical thickness of less than 0.1 have desirable properties, particularly at low angles of incidence. From the above expression, the $\lambda/10$ thickness of a dielectric with $\epsilon = 4$ is 0.059 inch at a frequency of 10,000 Mc. *

For certain space missions, the "zero wall" radome might prove more attractive than the half-wave radome because of the savings in weight.

*WADC Technical Report 57-67, "Techniques for Airborne Radome Design" (UNCLASSIFIED TITLE) September 1957 (CONFIDENTIAL).

Summary of Criteria for Material Selection

Based on the foregoing discussion, the following criteria, arranged in approximate order of importance, were chosen for the selection of candidate materials.

1. Electrical Properties
    a. Dielectric Loss
    b. Dielectric Constant
    c. Temperature Dependence of Dielectric Properties
2. Stability in Space Environment
    a. Temperature
    b. Vacuum
    c. Ultraviolet
3. Sealing Ability
    a. Gas Transmission (Leakage and Permeability)
    b. Attachment of Adjacent Structures
4. Thermal Radiative Properties
    a. Solar Absorptance
    b. Infrared Emittance
5. Structural Efficiency
    a. Strength
    b. Density.

CANDIDATE MATERIALS

GENERAL DISCUSSION

Candidate materials of two general types were considered:

1. Those material which, by themselves, would be expected to withstand the space environment.

2. Materials which would have to be protected in some manner in order to be utilized in the space environment. Such protection might consist of a thermal control paint to achieve and maintain a moderate temperature level in a substrate material with limited temperature resistance. Other types of protection might consist of an ultraviolet absorbing coating for a UV-sensitive substrate or a coating of laminated film for use with materials possessing an unsatisfactorily high gas permeability.

In the discussion of specific candidate materials which follows, the limitations of each material and the proposed modifications or protection recommended are given.

REINFORCED PLASTICS

Silicones

This material in the form of a properly fabricated fiberglass laminate has fair strength (room temperature flexural strength as high as 50, 000 psi) which should be adequate in the fabrication of a relatively thick, half-wave type radome. The dielectric loss of an E glass reinforced laminate is fairly low (about 0. 008), but can be made appreciably lower by the use of a reinforcement such as quartz cloth instead of the conventional E glass cloths. The resistance to UV is fair but can probably be improved by the use of UV-absorbing coatings or by the inclusion in the resin of additives which inhibit UV degradation. The gas permeability of silicone laminates, particularly those which have been postcured to improve high temperature properties, is probably high, but can be reduced either by high pressure impregnation with a resin, lamination with a low permeability film, or the application of a low permeability coating. If necessary, a thermal control paint can

be used to adjust the solar absorptance and IR emittance to acceptable values. A layer of thermal control paint sufficiently thick to change the thermal radiative properties to that of the paint itself will, of course, also effectively exclude UV radiation.

Methylated silicone resins have been found to be more resistant to UV than the conventional commercially available silicones. It was felt that a silicone resin of this type could be adapted for use in fabrication of a structural, reinforced laminate with improved UV resistance. Failing this, a silicone of this type could be used as a UV-resistant coating for plastics substrates with less UV resistance or could be used instead of potassium silicate as a binder in the formulation of thermal control paints with improved coating properties and structural integrity.

Polyesters

Polyesters based on triallyl cyanurate (TAC) and diallyl isophthalate (DAIP) should prove sufficiently heat resistant to be considered as candidate materials. The mechanical strength of glass cloth reinforced laminates based on these resins is relatively high. The following are typical values for flexural strength properties for 181 glass cloth laminates containing these resins:

TAC Laminates	
Flexural strength, room temperature	65-70, 000 psi
Flexural modulus, room temperature	3. 1-3. 9 x 10^6 psi
Flexural strength at 500° F, 1/2 hour at 500° F	35-45, 000 psi
Flexural modulus at 500° F, 1/2 hour at 500° F	2. 4-2. 7 x 10^6 psi
Flexural strength at 500° F, 192 hours at 500° F	35-45, 000 psi
Flexural modulus at 500° F, 192 hours at 500° F	2. 2-2. 6 x 10^6 psi
DAIP Laminates	
Flexural strength, room temperature	68, 000 psi
Flexural modulus, room temperature	3. 1 x 10^6 psi

Flexural strength, 400°F, 1/2 hour at 400°F	34,000 psi
Flexural modulus, 400°F, 1/2 hour at 400°F	2.7×10^6 psi

The dielectric loss is somewhat higher than that of corresponding silicone laminates but not excessively high (loss tangent = 0.01+). It should be possible to lower somewhat the dielectric loss by replacement of E glass cloth with quartz cloth. The resistance to UV is rather poor but can be improved by the use of UV-absorbing coatings or additives which inhibit UV degradation. The gas permeability, particularly that of the TAC polyester, may be too high, but can be decreased by the use of laminated films, coatings, or by resin impregnation. If required, a thermal control coating can be used to adjust the absorptance and emittance to desirable values and to exclude UV.

Phenyl Silanes

The strength properties are excellent. The following are typical strength values obtained from laminates based on phenyl silane resins:

Room temperature flexural strength	70-90,000 psi
Room temperature modulus in flexure	4.0×10^6 psi
500°F flexural strength, 1/2 hour at 500°F	70-78,000 psi
500°F modulus, 1/2 hour at 500°F	$3.0\text{-}3.6 \times 10^6$ psi
500°F flexural strength, 100 hours at 500°F	57-70,000 psi
500°F modulus, 100 hours at 500°F	$2.5\text{-}3.6 \times 10^6$ psi

The dielectric loss of an E glass-reinforced laminate is much higher than that of corresponding silicone or polyester laminates. Typical values of the loss tangent at X-band range from 0.02 to 0.025. In addition, the dielectric loss increases markedly with increasing temperature. The loss can be decreased slightly by the use of quartz cloth as a reinforcement instead of E glass.

The thermal stability at moderate temperatures is excellent as indicated by the retention of mechanical strength and dielectric properties after long term exposure to elevated temperatures. The absorptance

can be modified, if necessary, by the use of thermal control coatings. The gas permeability of a well made laminate will probably vary from poor to fair but can be lowered by the use of films, coatings, or impregnants.

Polyimides and Diphenyl Oxides

Polymers of this type are reported to have good electrical properties and excellent retention of physical properties when exposed to elevated temperatures.

Experimental Polyaromatic Polymer

One recently developed resin in the high temperature field is based on a polybenzimidazole polymer and is marketed under the name of Imidite.* Preliminary work to characterize the material has been almost entirely in the determination of structural properties. Resistance of the resin to degradation at high temperatures is outstanding, and it appears that reinforced laminates based on this resin system are the strongest plastic materials available for use in the 700°-1000°F range. For instance, E glass-Imidite laminates exhibit the following properties when tested at 700°F after several hours at 700°F.

Flexural Strength	70,000 psi
Flexural Modulus	4×10^6 psi
Compressive Strength (edgewise)	30,000 psi

The electrical properties of Imidite-fiberglass laminates at microwave frequencies have been found to be excellent over a wide range in temperature. In particular, the dielectric loss tangent of an Imidite-fiberglass laminate remains almost constant at 0.007 from room temperature to 600°F. Since Imidite laminates normally contain only 20 weight-percent of resin it is expected that a significant decrease in the dielectric loss could be achieved by the use of a low loss reinforcement such as quartz cloth in place of the conventional E glass cloth.

*Narmco Materials Division, Whittaker Corporation, Costa Mesa, California.

Gelatin

This material, developed at Wright Field, has several desirable physical properties. Laminates have been made which exhibit low permeability to helium, a flexural strength of 80,000 psi up to 400°F, and excellent UV resistance. Possible disadvantages in the use of such laminates might result from poor dielectric properties and moisture content resulting in excessive outgassing under hard vacuum conditions.

Ceramics

Two commercially available ceramic materials recommended for spacecraft antenna radomes are alumina and forsterite. Both materials have proved acceptable for a wide variety of microwave windows and special purpose radomes. Being rigid ceramics, they are more advantageously utilized than plastics in very high frequency microwave applications, e.g., from X-band through K-band where dimensional stability is highly critical. Close tolerances are easily maintained on small dielectric parts by grinding techniques. In addition, alumina and forsterite (if pure) have excellent resistance to UV degradation, outstanding erosion resistance, and satisfactory microwave properties which are insensitive to prolonged gamma and thermal radiation. They are readily metallized and brazed to metal waveguide structures to produce helium leak tight assemblies.

Alumina ceramics (Al_2O_3), with densities of 3.5 to 3.7 g/cc and a maximum use temperature of 1500°C, are chemically among the most stable and mechanically the strongest of the refractory oxides. Intricate shapes can be formed by slip casting, extruding, cold or hot pressing, or injection molding. The dielectric constant of commercial alumina ceramics ranges from 9 to 10, the loss tangent is less than 0.001, and the dielectric behavior is stable over a wide temperature range.

Forsterite ceramics with a density of 2.8 g/cc and a maximum use temperature of 1000°C, consist of 2 $MgO.SiO_2$ as the major crystalline phase, bonded with a glassy matrix. These ceramics are particularly useful as low loss dielectrics in designs where the lower dielectric constant of about 6 is desirable for lowering tolerance requirements in

high frequency microwave elements. Its relatively high thermal expansion is an advantage in metal-ceramic brazing. However, forsterite ceramics are quite poor in thermal shock resistance and have considerably lower strength than alumina ceramics. This might necessitate enclosing a forsterite radome within the spacecraft shroud rather than exposing it to direct aerodynamic heating.

Summary of Candidate Materials

The candidate materials chosen for the screening evaluation in this program are in two categories: Reinforced plastic laminates and ceramics. The specific types of candidate materials, trade names, and source of materials are summarized in the following table.

Type	Material	Trade Name	Source
Reinforced Plastic Laminates	Silicones	DC 2106 ARF Methylated Silicone	Dow-Corning Corp. (Prepared by Hughes Aircraft Co.)
	Triallyl cyanurate polyester	Vibrin 136A	Naugatuck Chemical
		P631	U.S. Polymeric Chemical
	Diallyl isophthalate polyester	P680	U.S. Polymeric Chemical
	Phenyl silanes	37-9X	Cincinnati Test Labs
		Resinox SC-1013	Monsanto Chemical Co.
	Diphenyl oxide	Doryl	Westinghouse
	Polyimides	PI-2101	DuPont
	Polybenzimidazole	Imidite	Narmco Industries, Inc.
	Gelatin	Superclear 300 Bloom Gelatin	Swift and Company
Ceramics	Forsterite		American Lava Corporation
	Alumina		American Lava Corporation

Table 1. Summary of candidate materials.

SCREENING EVALUATION TESTS

ELEVATED TEMPERATURE VACUUM STABILITY

The first screening test run on most of the candidate materials consisted of determining the stability at a pressure of 10^{-8} torr and a temperature of 350°F as indicated by the rate and amount of weight loss under these conditions. Test specimens consisted of small discs which were subsequently exposed to ultraviolet in vacuum. At least one specimen of each type was suspended from a calibrated quartz spring to enable weight measurements to be made continuously during vacuum exposure.

ULTRAVIOLET EXPOSURE

Those materials shown to be vacuum-stable were subjected to ultraviolet radiation in small vacuum cells. The effect of this exposure on the appearance, weight, and solar absorptance of the test specimens was noted.

PRELIMINARY DIELECTRIC MEASUREMENTS

Dielectric measurements were made on those materials for which dielectric properties were not already known. Those materials which were shown to have reasonable dielectric properties were subjected to further screening tests.

GAS TRANSMISSION

The gas transmission was determined for all of the materials which had passed the initial screening tests. Measurements were made on a three-inch diameter disc of the material contained in a special fixture as described in the section on Gas Transmission Tests. Tests were made using the fixture with a gas buret system to determine gross leakage. A relatively high value for the gas transmission did not eliminate a material from further consideration. Two methods for decreasing the gas transmission were considered.

High pressure impregnation with a polyester resin was used to decrease the gas transmission. Hughes Aircraft has had considerable experience in the impregnation of a particular type of thin-walled phenolic-fiberglass missile radome with polyester resin. By this method, the total leakage of these radomes has been reduced to less than 0.006 cubic centimeters of air per hour at a net pressure of one atmosphere. Expressed in more general terms, this corresponds to a leak rate for oxygen of approximately 50 μgm/day/meter^2/mm of thickness/cm. of mercury pressure difference. Lamination with plastic films with a relatively low gas permeability was also used to lower the gas transmission of plastic laminates. Polyvinyl fluoride and polytrifluoro-chloroethylene film were used to decrease gas transmission. All of these films were laminated to plastic laminates by the use of suitable adhesives.

EFFECT OF ULTRAVIOLET ON DIELECTRIC PROPERTIES

Dielectric specimens were subjected to ultraviolet radiation under a pressure of 10^{-8} torr. The effect of this exposure to UV and vacuum on the dielectric constant and loss was determined by making dielectric measurements before and after 1000 solar equivalent hours exposure. All dielectric measurements were made at room temperature in a resonant cavity type dielectrometer at a frequency of approximately 9280 Mc.

SUMMARY OF SCREENING TESTS

The following screening tests were used in evaluating the candidate materials:

- Stability at elevated temperature in vacuum.
- Effect of ultraviolet on absorptance.
- Dielectric measurements at room temperature.
- Gas transmission.
- Effect of ultraviolet on dielectric properties.

MATERIALS STUDIES

The materials studies conducted as part of this program were as follows:

- The Stabilization of Plastics for Use in a High Vacuum Environment.
- The Effect of Thermal Control Coatings on the Dielectric Properties of Radome Materials.
- The Improvement of Dielectric Properties by the Use of Quartz Reinforcement Instead of E Glass.
- A Comparison of Standard Silicone Laminate with Methylated Silicone Laminate (Effect of UV on Absorptance).
- An Investigation of Techniques to Decrease Gas Transmission.

EXPERIMENTAL

GAS TRANSMISSION TESTS

The gas transmission rate was determined for fiberglass laminates based on P680 (DAIP polyester), P631 (TAC polyester), Doryl (diphenyl oxide), gelatin, 37-9X and SC 1013 (phenyl silanes), DC 2106 (silicone) and PI-2101 (polyimide). All of the specimens consisted of three-inch diameter discs cut from three-ply or six-ply laminates. Each specimen was sealed to the gas transmission fixture with Apiezon W sealing compound as shown in Figure 1. Some materials were measured as laminated and others after a postcure cycle recommended to give optimum physical strength at elevated temperatures. All tests were made using air at one atmosphere pressure and a gas buret to measure the volume.

The lowest gas transmission rates were obtained for the two phenyl silane specimens and a Doryl specimen cut from a six-ply laminate. A postcured DC 2106 laminate and a PI-2101 laminate, both before and after postcure had leak rates too high to be determined. The lowest gas transmission rate obtained for an uncoated, unimpregnated laminate, 0.0002 cc/min/sq cm, was larger by three orders of magnitude than that previously obtained with an impregnated, thin-skinned phenolic fiberglass radome manufactured by Hughes Aircraft Company. It is concluded that resin impregnation or lamination with a low permeability film or both will be necessary for even the least porous of the plastics being considered in this program. The actual values obtained for air transmission for the various plastics are given in Table 2.

Two methods for decreasing the gas transmission were considered: impregnation with a catalyzed polyester resin followed by a high temperature cure and lamination with a low permeability film such as polyvinyl fluoride.

A six-ply P680 (DAIP) laminate with an air transmission rate of 1.3 cc/min/sq cm was impregnated with Laminac 4128 (styrenated alkyd catalyzed with Luperco ATC (50:50 benzoyl peroxide and tricresyl phosphate). In the process, the laminate immersed in the resin was subjected to a moderate vacuum for one hour followed by a pressure of

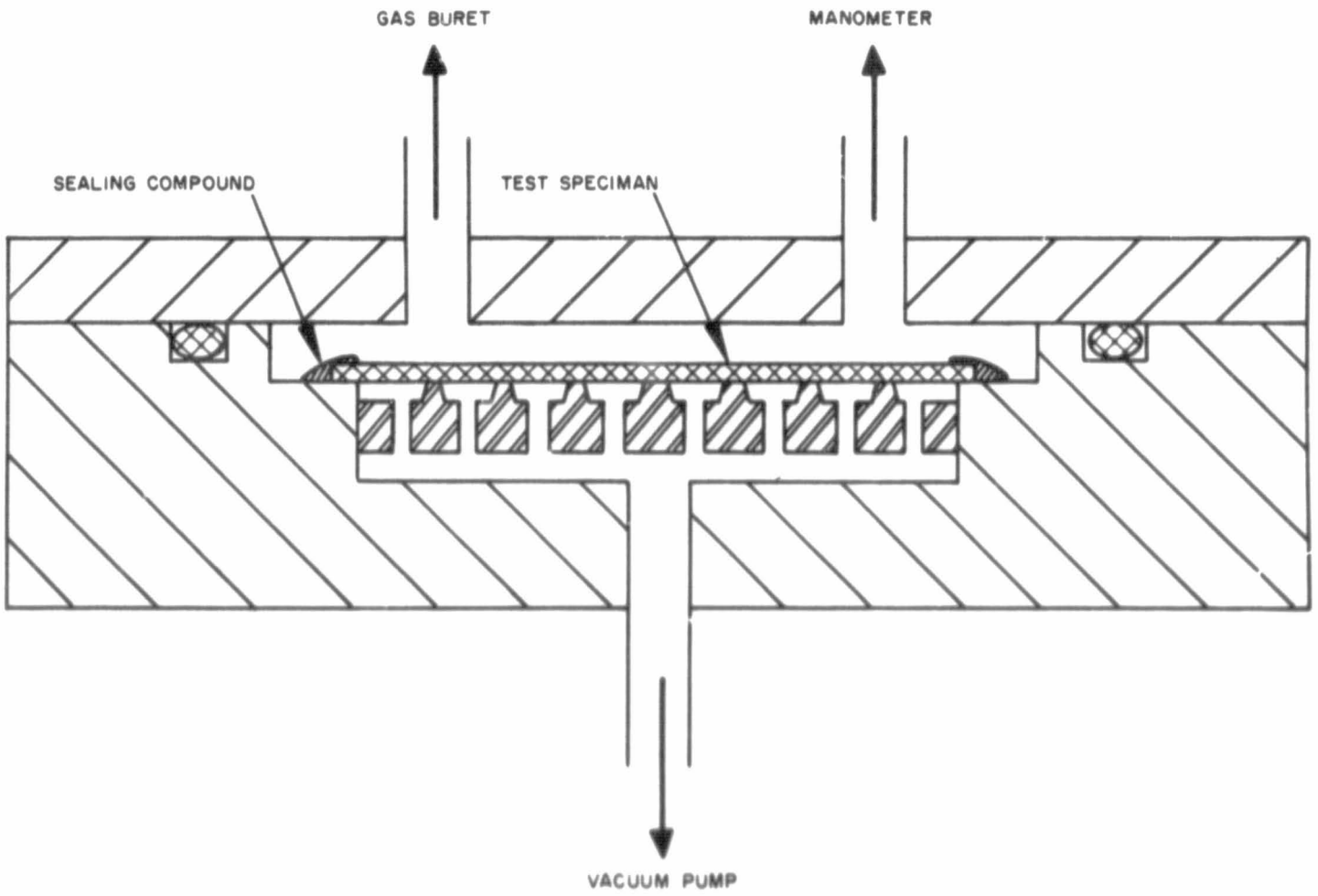

Figure 1. Diagram of gas transmission fixture.

Laminate Type	Number of plies	Air Transmission cc/min/sq cm
P680 (DAIP Polyester)	3	30
P631 (TAC Polyester)	3	0.05
Doryl (Diphenyl oxide)	3	26
Doryl (Diphenyl oxide)	6	0.0002
Gelatin	3	37
37-9X	3	0.0003
SC 1013	3	0.0003
DC 2106 (as laminated)	3	0.003
DC 2106 (postcured to 482°F)	3	Too high to measure
PI-2101 (polyimide) (as laminated)	3	Too high to measure
PI-2101 (postcured to 800°F)	3	Too high to measure

Table 2. Air transmission of plastics laminates.

500 psi for one hour. The excess resin was removed from the laminate using a ketone solvent and the impregnant remaining in the laminate was cured for one hour at 200°F. One such impregnation reduced the air transmission rate from 1.3 to 0.04 cc/min/sq cm.

A three-ply P680 laminate was laminated to a 2 mil thick film of Type A Tedlar (DuPont's polyvinyl fluoride) with an epoxy adhesive (R313 epoxy bonding kit manufactured by Carl H. Biggs Company). The bond line was cured for one hour at 260°F. This procedure reduced the leak rate from 30 to 0.0001 cc/min/sq cm.

In another experiment, a six-ply Doryl laminate was similarly laminated with a 6 mil layer of TFCE film which had been etched with a sodium-naphthalene-Tetrahydrofuran mixture according to a Hughes process specification in order to make it bondable. The leak rate was reduced from 0.0002 to 0.00003 cc/min/sq cm. This leak rate, though the lowest obtained, is larger than that obtained for a type of thin-skinned, phenolic fiberglass missile radome (2.5×10^{-7} cc/min/sq cm) by two orders of magnitude. These relatively low radome leak rates were obtained by conducting a series of vacuum-pressure impregnations with a polyester resin and, depending on the quality of the initial phenolic-fiberglass radome, required at least three to five separate impregnations. Table 3, which follows, summarizes the results.

Laminate Type	No. of Plies	Modification	Air Transmission cc/min/sq cm
P680 (DAIP)	6	none	1.3
		Impregnated with Laminac 4128	0.044
	3	none	30
		Laminated with 2 mil Tedlar	0.0001
Doryl (Diphenyl oxide)	6	none	0.0002
		Laminated with 6 mil TFCE	0.00003

Table 3. Air transmission of modified laminates.

THERMAL CONTROL COATINGS

EFFECT ON DIELECTRIC PROPERTIES

The effect of two thermal control coatings on the dielectric properties of a typical radome material was investigated. Dielectric specimens of Diall 794RA (a glass fiber, titanium dioxide filled diallyl phthalate molding compound manufactured by Mesa Plastics Company, West Los Angeles, California) were coated on one side with thermal control paint. One series of specimens was coated with a zinc oxide-potassium silicate mixture, while another was coated with a mixture of potassium silicate and an inorganic, white pigment developed at Hughes. In all cases, a sufficiently thick coating (about 0.006 inch) was applied to ensure opacity to ultraviolet radiation.

The values of dielectric constant and loss tangent calculated from measurements made at 9280 Mc did not show any significant effect as a result of the use of either of these coatings. The results are listed in Table 4. The two types of coating were measured approximately one month apart. The difference in dielectric constant over this period of time cannot be explained.

Sample No.	Type of Specimen	Dielectric Constant	Loss Tangent
553	Uncoated control	6.45	0.010
554	Coated with Hughes inorganic white	6.44	0.010
558		6.47	0.0098
553	Uncoated control	6.41	0.010
555	Coated with zinc oxide-potassium silicate	6.41	0.0093
556		6.41	0.010

Table 4. Effect of thermal control coatings on dielectric properties of Diall 794 RA.

As a result of these tests, polyesters and other UV-susceptible plastics will be considered more seriously as candidate materials for spacecraft dielectric windows. Certainly, a high degree of UV degradation of any material should not, by itself, eliminate any material from consideration as a candidate radome material.

EFFECT OF ULTRAVIOLET ON THERMAL CONTROL COATING

The effect of ultraviolet radiation on the solar absorptance of the Hughes inorganic white thermal control paint was determined up to a maximum exposure time of 1000 solar equivalent hours. The change observed was logarithmic in type, most of the change occurring in the first few hours of exposure. A particular coating had an initial absorptance of 0.15, which increased to 0.17 after 50 S.E.H., 0.18 after 200 S.E.H. and to 0.19 after a total exposure of 1000 S.E.H.

VACUUM STABILIZATION OF PLASTICS

SOLAR ABSORPTANCE SPECIMENS

A total of nine fiber glass-reinforced plastic specimens for solar absorptance measurements were conditioned under high vacuum at a temperature of 350°F. The specimens, which consisted of discs nominally 7/8 inch in diameter and 1/16-inch thick, were machined from laminates based on the following resins:

1. Imidite 1850, a polybenzimidazole from Narmco Materials Division, Whittaker Corporation
2. Resinox SC 1013, a phenyl silane from Monsanto Company
3. 37-9X, a phenyl silane from Cincinnati Testing Laboratories
4. P680, a diallyl isophthalate polyester, treated by U. S. Polymeric Chemicals
5. P631, a triallyl cyanurate polyester, treated by U. S. Polymeric Chemicals
6. DC 2106, a silicone from Dow Corning Corporation
7. A methylated silicone reported by Armour Research Foundation and prepared by Hughes Aircraft Company
8. PI-2101, a polyimide from DuPont
9. Doryl, a diphenyl oxide from Westinghouse Research Laboratories.

The vacuum conditioning served the dual purpose of screening materials for vacuum stability at elevated temperatures and stabilizing the specimens before subsequent exposure to ultraviolet radiation.

The method used in conditioning the specimens consisted essentially of removing the gross volatiles from the specimen by outgassing under high vacuum at room temperature and slowly increasing the temperature to 350°F while under the vacuum. This procedure was adopted to prevent flooding of the ion pumps with the resultant heating and loss of pumping efficiency.

The ultimate pressure attained and the time required to attain it was recorded for each type of material. Several specimens of each

type were stabilized, while at least one specimen of each type was suspended from a calibrated quartz spring balance to allow weight changes to be determined while under vacuum. Figure 2 shows the test setup with the heating elements removed for the sake of clarity. In addition, the specimens were weighed in air before and after conditioning to allow the calculation of the weight percentage loss under vacuum and to obtain an estimate of the amount of atmospheric moisture reabsorbed upon removal from the high temperature-vacuum environment. Table 5, which follows, summarizes the principal results obtained.

Resin System	Weight Loss at Room Temperature, Percent	Additional Weight Loss at 350°F, Percent	Total Weight Loss Measured in Vacuum, Percent	Time to Stabilize at 350°F, Days	Ultimate Pressure at 350°F, Torr	Total Weight Loss Measured in Air, Percent	Moisture Absorption, Percent
Imidite	0	0.87	0.87	3	2×10^{-8}	0.79	0.08
SC 1013	0.30	0.24	0.54	3	2×10^{-7}	0.29	0.25
37-9X	0.60	0.42	1.02	3	4×10^{-7}	0.27	0.75
P680	0	1.35	1.35	5	5×10^{-8}	0.68	0.67
P631	0	0.98	0.98	13	4×10^{-8}	1.01	0
DC 2106	0.66 (0.40)	1.30 (0.40)	1.96 (0.80)	3 (12)	2×10^{-8} (1×10^{-8})	0.14 (0.10)	1.82 (0.70)
Methylated Silicone	0	1.04	1.04	7	1×10^{-8}	0.47	0.57
PI-2101	0.63	0	0.63	1	1×10^{-8}	0.14	0.49
Doryl	0	0.43	0.43	12-14	2×10^{-8}	0.38	0.05

Table 5. Vacuum stabilization of plastic laminates.

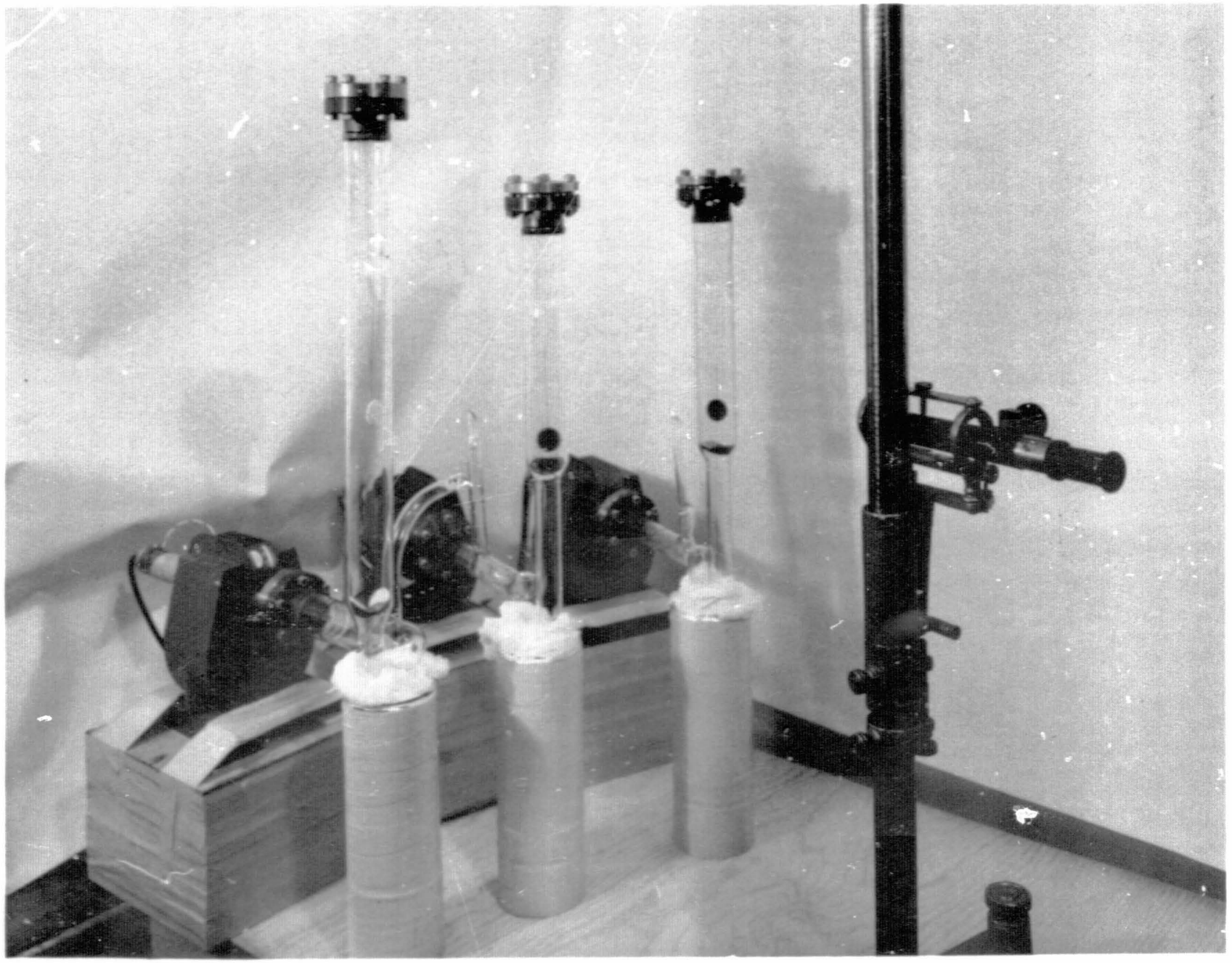

Figure 2. Vacuum stabilization of plastics.

The first weight loss data reported for the DC 2106 test specimens was highly questionable. The conditioning procedure was repeated for this material; the results are shown in parentheses in the table.

Some general conclusions can be drawn from the foregoing results. Most of the plastics tested exhibited a fair degree of stability after an initial period during which a moderate degree of outgassing took place. However, the relatively high equilibrium pressures obtained in the case of the SC 1013 and 37-9X indicate the presence of undesirable volatile constituents in these materials. The figures in the last column of the preceding table are subject to uncertainty due, in part, to the uncertainty in determining the weight loss during conditioning. The moisture absorption upon repressurization also depends on the humidity, the length of time between repressurization and the final weighing in air. The test results prove that most of the plastics, except for the Imidite, Doryl (diphenyl oxide) and P631 (TAC polyester) contain somewhat less moisture and other volatiles at equilibrium with a hard-vacuum environment than under ordinary atmospheric conditions.

VACUUM CONDITIONING OF DIELECTRIC SPECIMENS

A series of reinforced plastics dielectric specimens based on DC 2106 (silicone), P680 (DAIP polyester), P631 (TAC polyester), and Imidite 1850 (reinforced in one case with E glass and in the other with J. P. Stevens Quartz cloth) was stabilized under vacuum at high temperature. The specimens were stabilized over a period of 12 days at 10^{-6} torr at a temperature of 350°F. A mercury-diffusion pump with a nominal capacity of 75 liters per second was used along with a liquid nitrogen trap. Relatively large quantities of water and other volatile substances were trapped during this period.

Following vacuum stabilization, both faces of each specimen were ground to ensure flatness and parallelism within 0.001 inch. All specimens were approximately one-half wavelength thick.

The dielectric constant and loss tangent of each specimen were calculated from resonant cavity measurements made at 9280 Mc under ordinary atmospheric conditions. The dielectric properties obtained are given in Table 6.

Material	Dielectric Constant		Loss Tangent	
	Side 1	Side 2	Side 1	Side 2
DC 2106	4.27	4.27	0.0064	0.0065
P680	4.46	4.46	0.0090	0.0091
P631	5.06	5.08	0.0092	0.0090
Imidite 1850 (E glass)	4.65	4.65	0.0069	0.0066
Imidite 1850 (Quartz)	3.38	3.38	0.0056	0.0063

Table 6. Dielectric properties of vacuum-stabilized plastics.

Following the measurement of the initial dielectric properties, an attempt was made to vacuum stabilize the two types of Imidite specimens in small irradiation-chamber/ion-pump assemblies. After several days pumping, it did not appear practical to stabilize these specimens using these small ion pumps. Pressures in the 10^{-4} torr range were obtained after several days pumping at room temperature. The specimens could not be heated to promote outgassing since this procedure would have resulted in flooding the ion pumps with attendant heating.

The specimens were finally stabilized at 350°F in the 10^{-8} torr pressure range using ion pumps with a capacity of 75 liters per second. The specimens were then irradiated on one side only for 1000 solar equivalent hours. The chambers containing the specimens were repressurized using dry nitrogen and the specimens were stored over desiccant until measured in the dielectrometer.

The electrical measurements were made as before at 9280 Mc. The consistency of results indicated that virtually no warping had taken place as a result of the vacuum-ultraviolet conditioning. However, both the dielectric constant and loss tangent of the two types of Imidite were

found to have decreased markedly. The results obtained are shown in Table 7:

Type of Specimen	Side	Dielectric Constant	Loss Tangent
Imidite – E glass	1	4.37	0.0039
	2	4.38	0.0040
Imidite – Quartz	1	3.13	0.0026
	2	3.13	0.0025

Table 7. Dielectric properties of irradiated Imidite laminates.

EFFECT OF ULTRAVIOLET ON SOLAR ABSORPTANCE

Test specimens of the nine fiber glass-reinforced plastics, vacuum-stabilized as described in the previous section, and specimens of three commercially available ceramics were exposed to ultraviolet radiation of 5 times solar equivalent up to a maximum exposure time of 1000 solar equivalent hours. The effect of this exposure on the solar absorptance and on the weight loss (qualitatively) was determined. In addition, the change in physical appearance was observed.

The source of the ultraviolet radiation was a BH-6 high pressure mercury arc lamp. Figure 3 shows the approximate configuration of the vacuum chamber and the lamp, while Figure 4 shows a typical test setup with four test specimens being exposed simultaneously.

The solar absorptance measurements were made in a Gier-Dunkel reflectometer integrating sphere over the wavelength range from 0.3 to 2.7 microns in 10 percent incremental steps following the Johnson curve of solar emission. The data obtained is not as accurate as a 50 point determination but is adequate for screening. The data required to calculate a 10 point absorptance value is obtained by measuring the reflectance at the ten selected points over the specified range. The reflectance standard is magnesium oxide which is remeasured each day.

Figure 5 shows schematically the auxiliary optics required in the operation of the integrating sphere. The detector is not shown in the integrating sphere since it is 90 degrees in front or in back of the plane

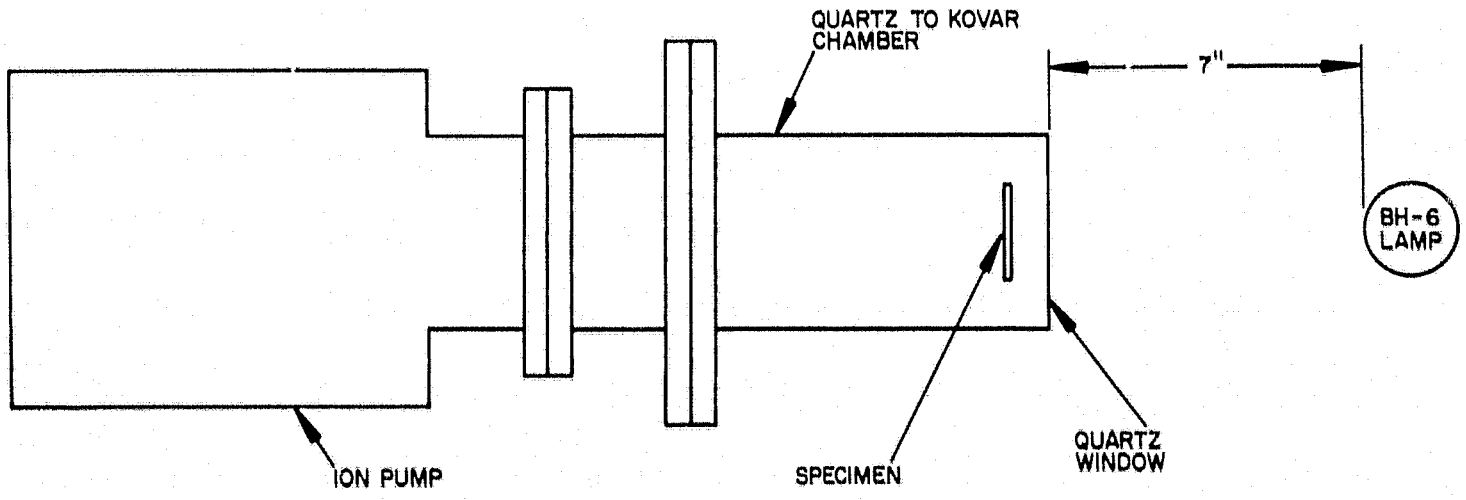

Figure 3. Test setup – irradiation of test specimens.

Figure 4. Irradiation of test specimens under high vacuum.

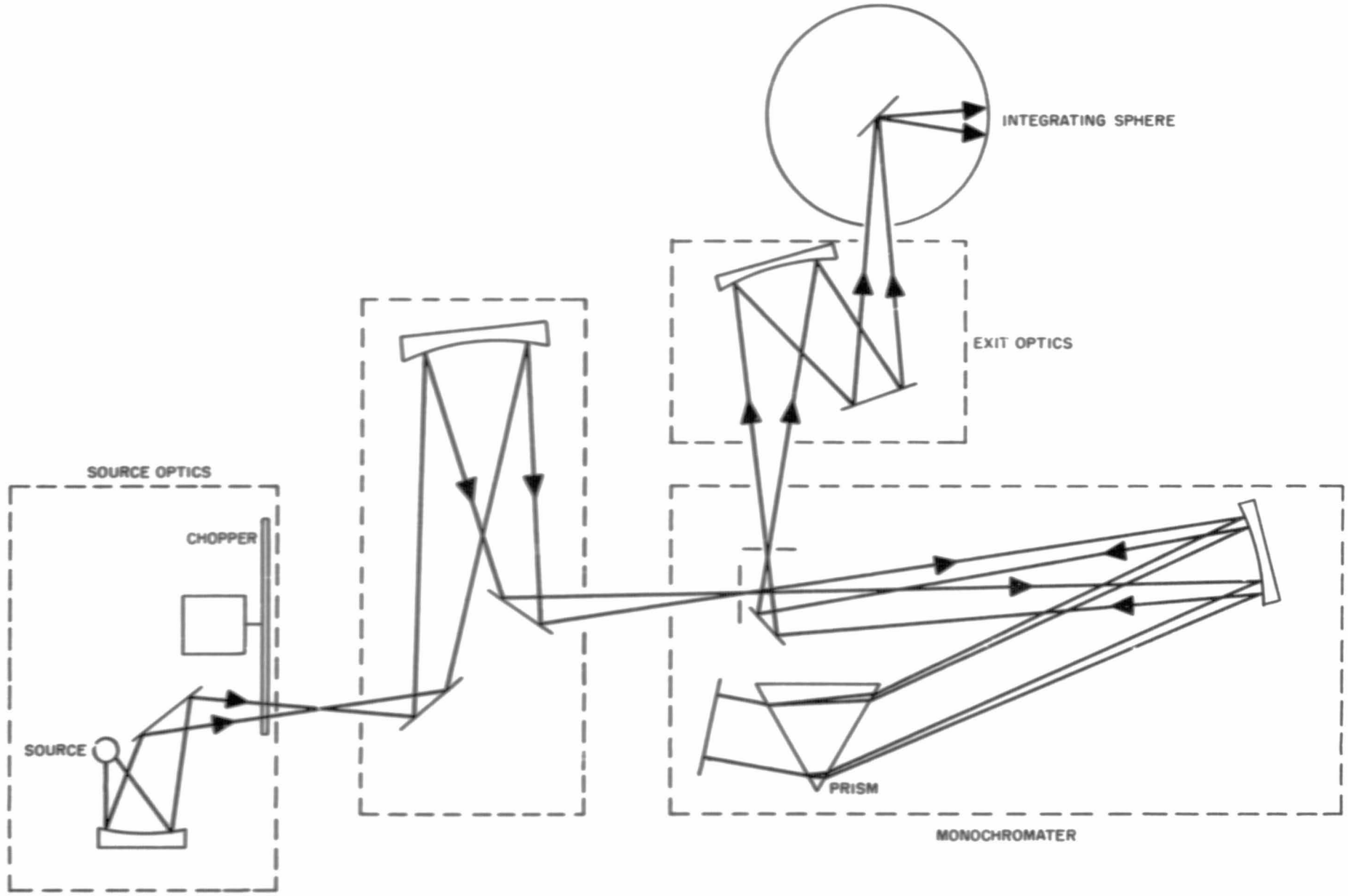

Figure 5. Integrating sphere auxiliary optics.

of the paper on the sample-sphere axis. This is done to take advantage of the two bounce technique whereby the whole surface of the sphere is illuminated by the second reflection, thus avoiding large errors due to specularity of the sample. Figure 6 shows the apparatus in operation.

Each of the test specimens had one machined surface with the other surface left as laminated. The Imidite, SC 1013 and DC 2106 specimens were measured on both sides prior to ultraviolet exposure. The remainder of the measurements were made on the machined side only.

The laminates least affected by the ultraviolet conditioning were those based on Imidite, 37-9X, PI-2101 and Doryl. The calculated values for absorptance of both the 37-9X and the PI-2101 were found to have decreased perhaps due to a bleaching effect of the radiation. The other materials underwent a pronounced change in solar absorptance as a result of 1000 solar equivalent hours exposure. The methylated silicone was not more UV stable than the DC 2106 as had been anticipated. On the contrary, the absorptance change was more pronounced for the methylated silicone than for the DC 2106. All of the specimens underwent a change in color with the exception the specimens based on Imidite, PI-2101 and Doryl, all of which were relatively dark before and after conditioning.

Weight measurements made in air following irradiation, did not indicate any substantial weight loss. Small weight changes would only be detectable by suspending the specimens by a quartz spring balance during irradiation.

The infrared emittance was determined in a heated hohlraum prior to ultraviolet irradition. The specimens were not remeasured after ultraviolet radiation and the emittance was assumed to remain the same.

A summary of the principal test results obtained for the plastic laminates is given in Table 8.

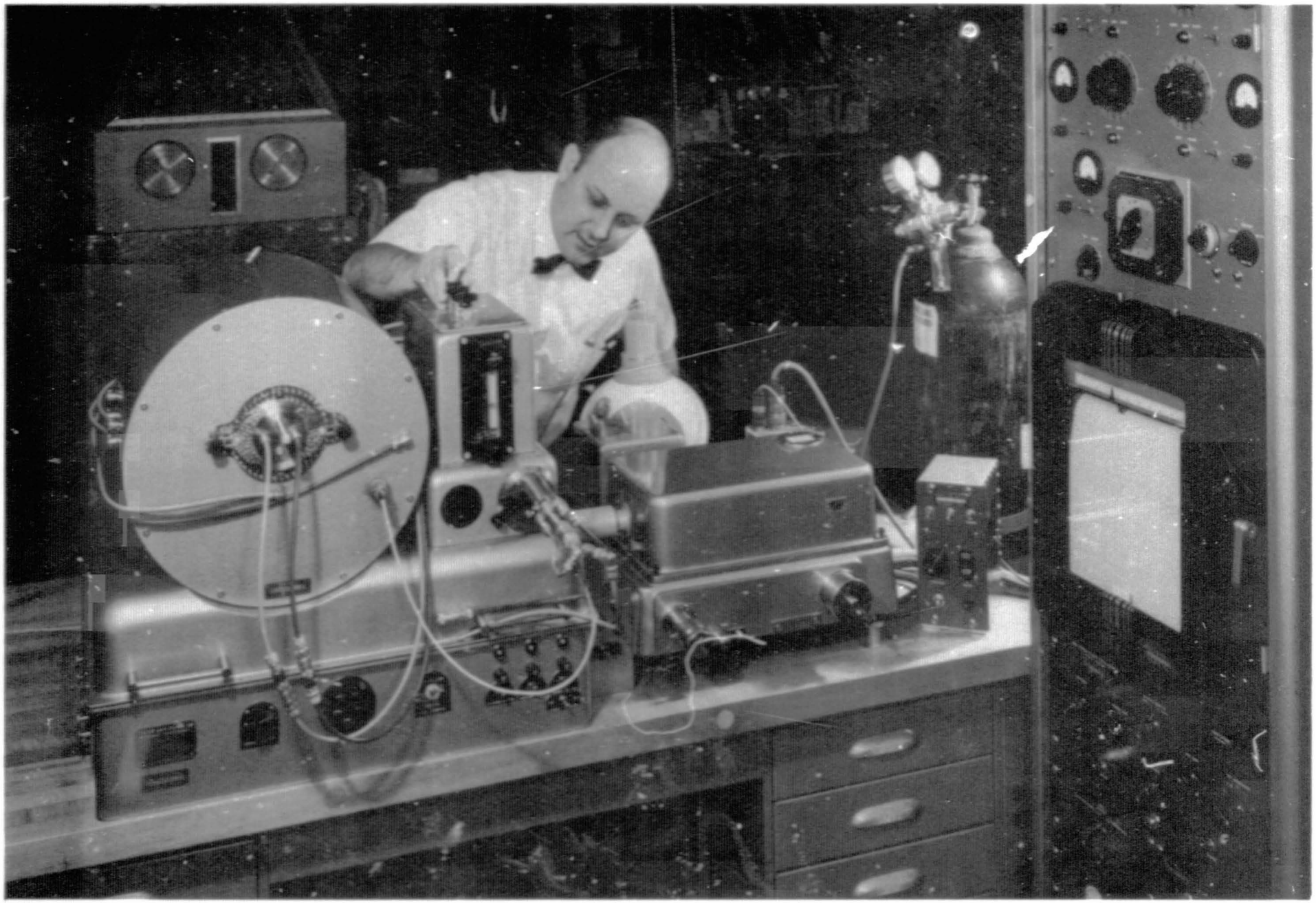

Figure 6. Gier-Dunkel integrating sphere in operation.

Laminate Type	Solar Absorptance After Exposures in S. E. H. of			Initial Emittance	Change in Color
	0	100	1000		
Imidite	0.69 (0.81)	0.71	0.71	0.80	None
SC 1013	0.56 (0.81)	0.60	0.67	0.80	Tan to light brown
37-9X	0.80	-	0.78	0.86	Tan to light brown
P 680	0.57	-	0.70	0.84	Light green to brown
P 631	0.46	-	0.65	0.84	Green-tan to brown
DC 2106	0.41 (0.46)	0.49	0.54	0.79	White to lemon yellow
Methylated Silicone	0.33	-	0.49	0.80	White to lemon yellow
PI-2101	0.75	-	0.72	0.87	None
Doryl	0.83	-	0.83	0.78	None

Table 8. Effect of ultraviolet radiation on the absorptance of plastics laminates.

Test specimens of three ceramics from American Lava Corporation, Al Si Mag 243 (forsterite), Al Si Mag 748 (98 percent alumina) and Al Si Mag 753 (99.5 percent alumina), were also tested for stability to ultraviolet radiation. Discs of these materials 1/8 inch thick and 7/8 inch in diameter were exposed to ultraviolet for 10, 100 and 1000 solar equivalent hours and the effect on the solar absorptance determined. A different specimen was taken for each exposure time, therefore, a "before" and "after" value of solar absorptance is given for each exposure time for each material. During the exposure, the forsterite yellowed slightly while both types of alumina turned lemon yellow. The absorptance of the forsterite was virtually unaffected by the ultraviolet exposure while this property was affected considerably in the case of the two aluminas. The purer alumina was affected more than the other. The complete results are given in Table 9 which follows:

Material	Solar Absorptance After Exposure in S. E. H. of					
	10		100		1000	
	Before	After	Before	After	Before	After
Al Si Mag 243 (forsterite)	0.47	0.46	0.46	0.47	0.46	0.47
Al Si Mag 753 (99.5 % Al_2O_3)	0.20	0.32	0.17	0.30	0.18	0.33
Al Si Mag 748 (98% Al_2O_3)	0.19	0.27	0.18	0.25	0.16	0.25

Table 9. Effect of ultraviolet radiation on the absorptance of ceramics.

HIGH VACUUM DIELECTRIC MEASUREMENTS

The Hughes X-band resonant cavity dielectrometer is designed to operate at atmospheric pressure. This is a serious disadvantage when attempting to investigate the effect of simulated space conditions (hard vacuum and solar radiation) on the dielectric properties of reinforced plastics. All of the plastics being considered in this program absorb a varying amount of moisture under ordinary atmospheric conditions. Since the effect of simulated solar radiation under hard vacuum is being investigated, it becomes necessary to vacuum stabilize the material following each dielectric measurement prior to irradiation. Making dielectric measurements at atmospheric pressure also introduces an unknown variable into the test results; that is, the effect of absorbed moisture on the dielectric properties.

The foregoing considerations prompted the investigation of the practicability of operating a resonant cavity type dielectrometer under conditions of hard vacuum. Dielectric measurements were made at atmospheric pressure and under hard vacuum on two standard ceramic dielectric specimens, fused silica and pyroceram. Plastics specimens were not measured to avoid possible contamination of the vacuum chamber.

Figure 7 gives a block diagram of the equipment used in making the measurements. In Figure 8, the vacuum chamber is open to show the resonant cavity. In Figure 9, the vacuum chamber is shown closed and ready for measurement. The micrometer drum was rotated by means of shaft extending through a hermetic rotating seal mounted in the wall of the vacuum chamber and connected to a right angle drive mechanism. A small periscope was mounted in the vacuum chamber to enable reading the micrometer through the vacuum chamber viewing port.

All measurements were made at a frequency of 9280 ± 1 Mc. The cavity temperature was monitored by means of a thermocouple. All measurements were made in the temperature range of 72.5° to 75.5°F.

The results of a total of 38 measurements, 17 on the pyroceram and 21 on the fused silica, showed no significant difference in the calculated values of the dielectric properties. Table 10, which follows,

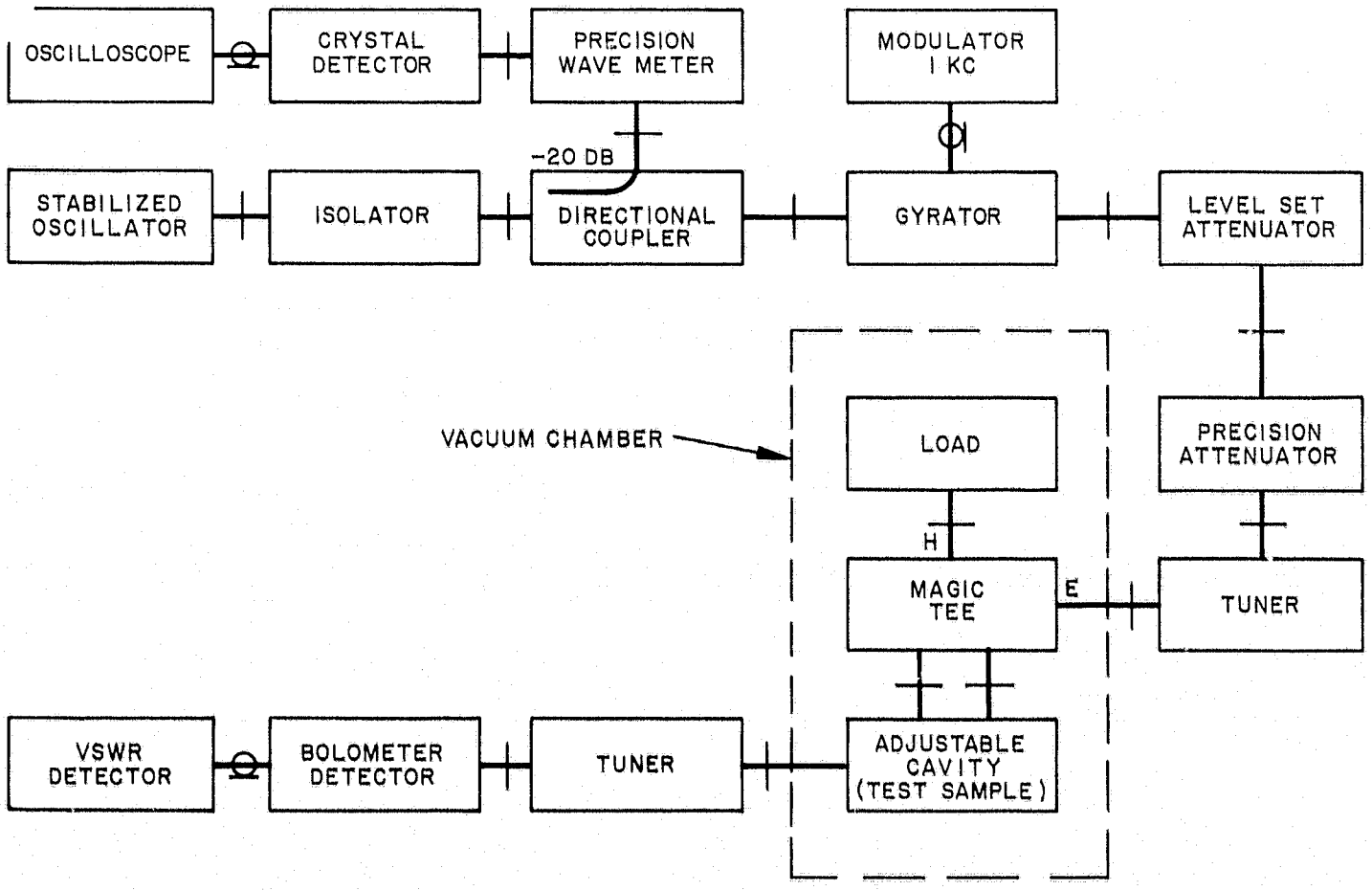

Figure 7. Block diagram for measuring dielectric constant and loss tangent.

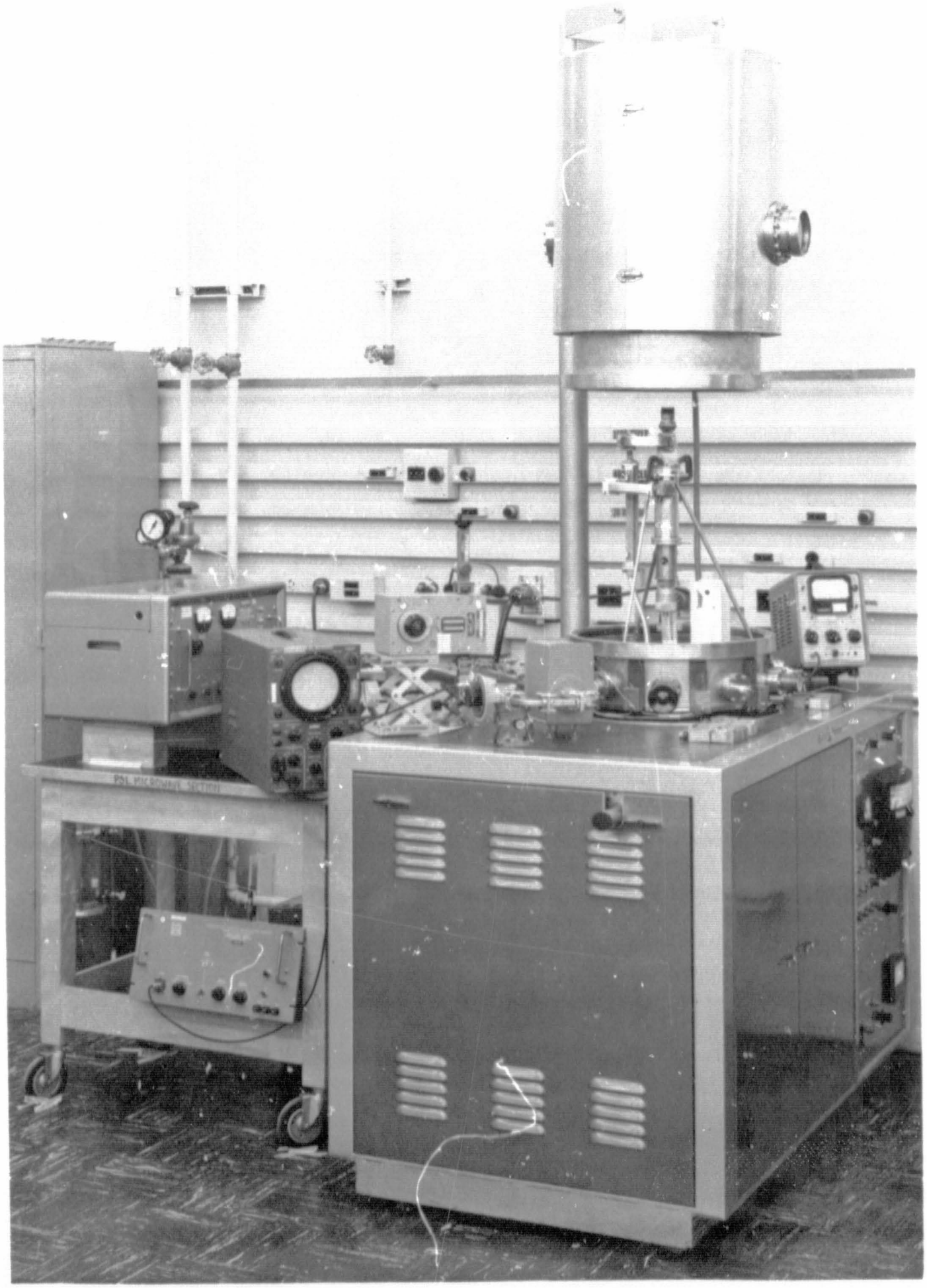

Figure 8. High vacuum dielectrometer – chamber open.

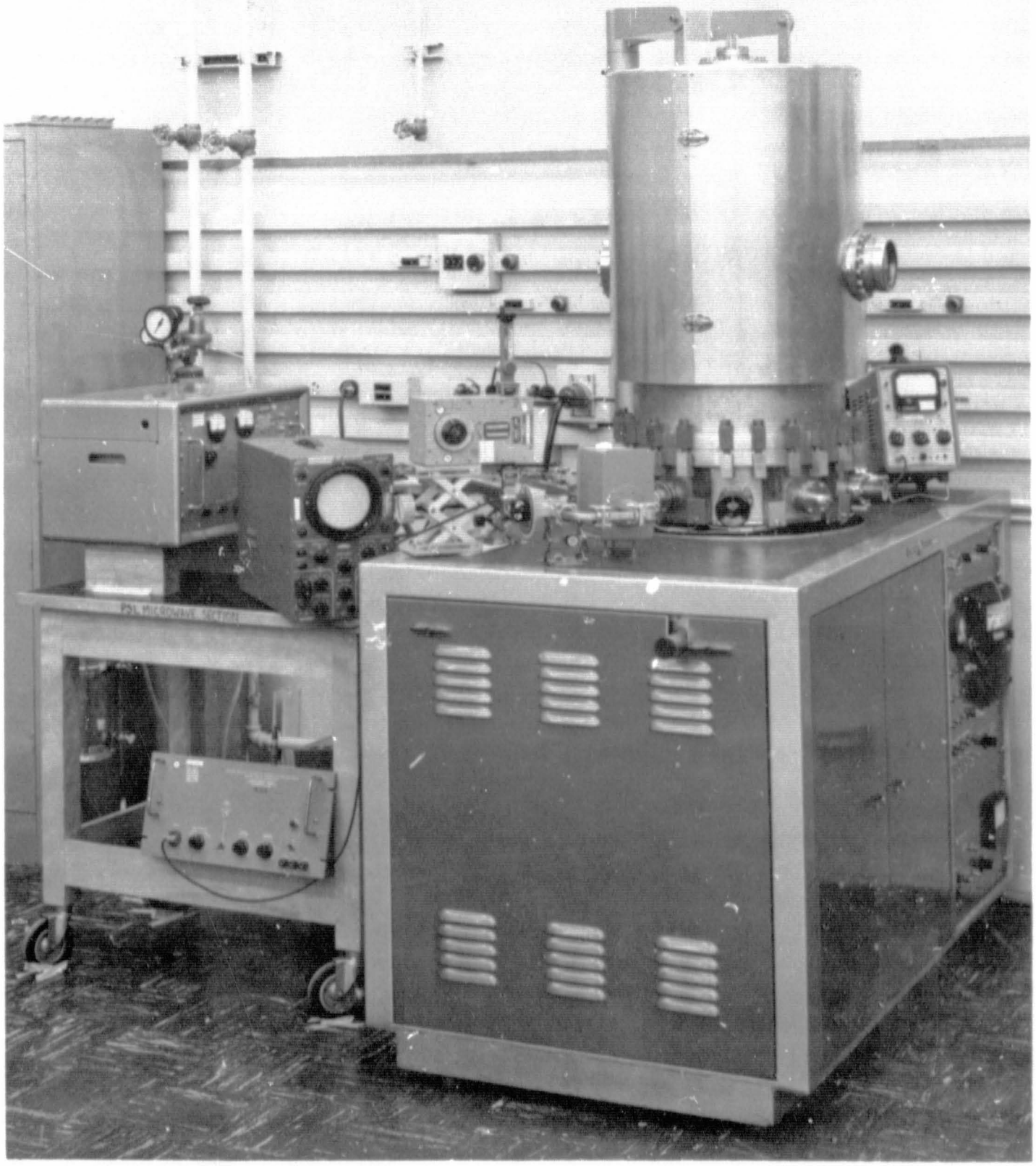

Figure 9. High vacuum dielectrometer - chamber closed.

gives the average values of dielectric constant and loss tangent for the two specimens for each pressure (the complete results recorded in the order corresponding to that in which the original measurements were made are tabulated in the Appendix).

Specimen Type	Pressure, Torr	Dielectric Constant	Loss Tangent, x 10^4
Pyroceram	760	5.7442	4.44
	10^{-8}	5.7451	4.50
Fused Silica	760	3.8296	1.48
	10^{-8}	3.8298	1.62

Table 10. High vacuum dielectric measurements.

It may be concluded from the foregoing results that the operation of a resonant cavity-type dielectrometer in a hard vacuum is practical. However, the use of a conventional resonant cavity in a vacuum chamber would still require transfer of the specimens from the cavity to the radiation cell with the attendant absorption of moisture. A good solution would be the fabrication of a high vacuum resonant cavity with provisions for irradiation of the specimen while in position in the cavity. Dielectric measurements could be made before, during and after exposure to ultraviolet. The dielectrometer could be designed to allow exposure of the dielectric specimen to various types of particle radiation.

EFFECT OF LOW LOSS REINFORCEMENT ON DIELECTRIC PROPERTIES OF PLASTIC LAMINATES

The dielectric constant and loss tangent at 9280 Mc were determined for DC 2106 laminates reinforced with S (994) glass cloth and D (556) glass cloth. The results were compared with those obtained previously for DC 2106 laminates reinforced with E glass cloth and quartz cloth (General Electric). The dielectric properties were also calculated from measurements made at 9280 Mc on specimens prepared from Imidite laminates, both containing nominally 20 weight-percent resin. One laminate contained 181 E glass cloth and the other contained style 581 quartz cloth supplied by J. P. Stevens. Surprisingly, the loss tangent of the quartz-reinforced Imidite was only slightly lower than that of the E glass-reinforced Imidite prior to irradiation under vacuum. The dielectric constant of the quartz laminate was much lower than that of the E glass laminate, as was expected. Table 11 gives the dielectric properties for each type of laminate.

Type of Laminate	Dielectric Constant	Loss Tangent
DC 2106 - E glass	4.27	0.0065
DC 2106 - quartz	3.30	0.0035
DC 2106 - D glass	3.39	0.0020
DC 2106 - S glass	3.74	0.0085
Imidite - E glass	4.65	0.0067
Imidite - quartz	3.38	0.0059

Table 11. Dielectric properties of fiber glass laminates.

MISCELLANEOUS DIELECTRIC TEST RESULTS

Dielectric measurements at 9280 Mc were made on E-glass reinforced laminates based on gelatin (Superclear 300 from Swift and Company), Doryl (diphenyl oxide from Micarta Division of Westinghouse), and PI-2101 (polyimide from Du Pont).

The loss tangent obtained for the gelatin laminate was somewhat higher (0.018) than that considered desirable in a material for a radome application. The relatively high dielectric loss along with the extremely high porosity and apparently poor mechanical strength properties prompted removal of this material from further consideration.

Both the Doryl and the PI-2101 laminates had loss tangent values sufficiently low (0.005 and 0.011, respectively) to merit their further consideration as candidate materials. The dielectric constant of the PI-2101 was somewhat low (3.4 to 3.6). This was due to extreme porosity of the resin matrix (about 50 volume percent of voids).

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Several conclusions may be drawn from the results of the screening evaluation and materials studies:

1. Several cured plastics exhibit a fairly high degree of vacuum stability after an initial period of outgassing. These include silicones, diphenyl oxide, polyimide and Imidite. The two polyesters tested had fair stability while the two phenyl silanes had poor stability.

2. The solar absorptance of most of the plastics and the three ceramics was affected considerably by ultraviolet irradiation. In general, the absorptance of the lighter colored plastics such as the silicones and the polyesters changed the most while that of the darker plastics either changed very little or decreased. This latter result may have been due to a "bleaching" effect.

3. There is an indication that ultraviolet irradiation decreased both the dielectric constant and loss tangent of Imidite dielectric specimens. However, the results are subject to errors of unknown magnitude, since the specimens were exposed to ultraviolet in vacuum and subjected to dielectric measurements at atmospheric pressure. One logical solution to this problem would be the design and fabrication of a dielectrometer which can be operated under hard vacuum and is designed to allow irradiation of specimens while in place in the dielectrometer.

4. The results obtained on gas transmission indicate that any of the reinforced plastics tested will leak too fast without some modification such as resin impregnation or lamination with a low permeability film.

5. Control of the thermal radiative properties of a radome structure without affecting adversely the electrical properties was shown to be feasible.

Future work will be principally concerned with the following:

1. The effect of hard vacuum and ultraviolet for more prolonged periods on the thermal radiative and dielectric properties of plastics and ceramics both unprotected and protected by thermal control coatings.

2. The boresighting of actual radomes fabricated from those plastics and ceramics shown, in the preliminary screening evaluation, to be suitable in the space environment. Boresighting tests on radomes coated with thermal control coatings and modified to have low gas permeability.

APPENDIX

PREPARATION OF THE FIBER GLASS LAMINATES

The laminates for this program were made in a manually operated laboratory press using either the laminating conditions recommended by the manufacturer or those based on our experience and observations. For those cases in which it was necessary to coat our own cloth, the manufacturer's recommendations were followed in initial coating runs and were modified if necessary to improve the quality of the resulting laminates.

Table 12 summarizes the conditions used in preparing the laminates.

Material	Coating Conditions		Laminating Conditions			Postcure Conditions		Approx Resin Content, wt-%
	Time Minutes	Temp °F	Time Minutes	Temp °F	Pressure psi	Time Hours	Temp °F	
P680	Obtained as Prepreg	30	30	275	300	No Posture		35
P631	Obtained as Prepreg		30	275	140	6 16	275 350	35
37-9X	Obtained as Prepreg		2.5 60	300 300	0 400	PC No. 1		26
SC 1013	Obtained as Prepreg		0.75 60	300 300	0 400	24 24 24	250 300. 350	30
Doryl	Obtained as Prepreg		45 120 120	300 300 500	0 800 800	PC No. 2		20
PI-2101	Obtained as Prepreg		120	700	125	PC No. 1		20
Imidite	Obtained as Prepreg		60	700	200	PC No. 3		20
Methylated Silicone	60	Room Temp	15 60	300 350	20 100	4 2	350 400	20
DC 2106	20	200	60	350	300	PC No. 4		30
Gelatin	45	Room Temp	60	220	625	none		20

PC No. 1: Postcured 18 hours at 275°F, 48 hours from 275°to 400°F and 4 hours at 400°F.

PC No. 2: Temperature increased from 250° to 500°F over period of 144 hours.

PC No. 3: Postcured in nitrogen as follows: 24 hours each at temperatures of 600°, 650°, 700° and 750° F, 8 hours at 800°F, and 3 hours at 700°F.

PC No. 4: Postcured 24 hours at 302°F, 24 hours at 392°F and 72 hours at 482°F.

Table 12. Fabrication conditions for plastics laminates.

Specimen Type	Temperature, °F	Pressure, Torr	Dielectric Constant	Loss Tangent x 10^{-4}
Pyroceram	73.0	760	5.7450	5.13
	73.5	8×10^{-9}	5.7421	4.14
	73.5	8×10^{-9}	5.7421	4.14
	73.5	8×10^{-9}	5.7480	3.81
	73.5	8×10^{-9}	5.7429	5.44
	73.5	760	5.7433	3.51
	73.5	760	5.7438	5.13
	74.0	9×10^{-9}	5.7460	4.47
	74.0	760	5.7440	3.51
	74.0	760	5.7444	4.16
	74.0	760	5.7460	5.45
	74.0	760	5.7434	4.48
	74.0	760	5.7435	4.16
	74.5	9×10^{-9}	5.7462	4.79
	75.0	9×10^{-9}	5.7460	4.47
	75.0	9×10^{-9}	5.7464	5.12
	75.5	9×10^{-9}	5.7458	4.14
Fused Silica	72.5	760	3.8303	1.50
	72.5	760	3.8292	1.50
	73.0	760	3.8304	1.43
	73.5	8×10^{-9}	3.8294	1.63
	73.5	8×10^{-9}	3.8295	1.63
	73.5	760	3.8286	1.51
	73.5	760	3.8286	1.51
	73.5	760	3.8297	1.50
	74.0	8×10^{-9}	3.8295	1.63
	74.0	9×10^{-9}	3.8296	1.63
	74.0	760	3.8298	1.50
	74.0	760	3.8300	1.31
	74.0	760	3.8295	1.44
	74.0	760	3.8292	1.63
	74.5	9×10^{-9}	3.8298	1.63
	74.5	9×10^{-9}	3.8297	1.63
	75.0	9×10^{-9}	3.8298	1.63
	75.0	9×10^{-9}	3.8298	1.63
	75.0	9×10^{-9}	3.8300	1.50
	75.0	9×10^{-9}	3.8302	1.63
	75.5	9×10^{-9}	3.8302	1.63

Calculated dielectric properties of dielectric standards measured under atmospheric pressure and hard vacuum.